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Maximizing solar PV energy penetration using energy storage technology

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ABSTRACT

Many countries around the world are considering using solar energy technologies in their future energy planning. The intermittency and unpredictability nature of solar power generation, which can influence the power quality and reliability of the power grid especially at large-scale solar energy systems, constitute a drawback for use of solar technology. Precise research and investigations are needed to overcome this weakness helping solar power be used in power network in large scale.

The variation in sun radiation may lead to over-production of electricity from solar PV generators at one time, and lack of production to satisfy the energy demand at another time. As a result, solar PV systems demonstrate a low-level of reliability in power systems. However, an energy storage technology would play a significant role in increasing the reliability of solar power generation systems.

The objectives of this study are: firstly to review the issues in relation to grid-integration of solar PV systems, secondly, to review a range of storage devices that could technically and economically be used in association with solar PV energy in order to increase the solar energy penetration level with appropriate reliability in weak electric systems, and finally to present a model for solar PV system combined with battery and super-capacitor.

Contents

1. Introduction

According to IEA-PVPS, worldwide solar PV market has experienced enormous growth. Solar energy has the potential to play a crucial role in the world's energy supply. The last 10 years has been a period when PV energy changed from being a small-scale contributor to energy supply to being a more substantial one, and the next 10 years look like being a period when the solar energy technology could have an even more substantial impact.

By end of 2007 the cumulative installed capacity of solar PV system reached 92,000 MW worldwide [1]. This was about 500 MW at the end of 1994. The global development of PV capacity has been shown in Fig. 1. According to this figure, installation of solar PV system has been growing at an annual average of more than 25% since 1994. Experts believe that through

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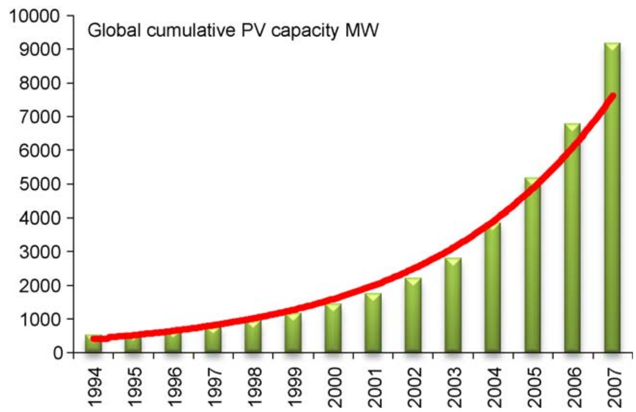

Fig. 1. Global PV energy capacity.

increased production volume and improved PV technology we will observe a much faster increase in solar PV market.

Important role of solar energy in energy mix is noticeable; however, the intermittency nature of the solar energy is considered as one of the weaknesses of utilization of this technology. Using energy storage in connection with solar power systems is widely recognized as a reasonable solution to compensate this weakness at both small scale and large scale. The work described in this paper highlights the need to store energy in order to strengthen power networks and maintain load levels. There are various storage technologies some in use and some in development. An appropriate storage device with sufficient storage capacity will allow a grid-connected solar PV system to perform much better and to minimize the negative impacts on the grid's power quality and to maximize penetration level.

2. Conventional power supply

At present, the production of electricity is highly centralized and often a long distance away from its end users [2]. The conventional power networks can be described as:

- Centralized power generation.
- Controllable generation, un-controllable loads.
- Generation follows the load.
- Limited grid access for new producers.
- Power networks are half a century old.
- Power flows in only one direction.
- Power system operation is mainly based on historical data and experience.
- Overloads in the system are detected by the operators.
- Rerouting of power flow in the case of overload is performed by the operators.
- Utilities do not have sufficient information about the grid conditions.
- High power loss.
- Likely events of costly power blackout, etc.

3. Distributed energy resources

Distributed energy resources (DER) cover a wide range of non-renewable energy technologies, as well as renewable energy technologies. Distributed generation systems deliver electric power through smaller-sized generators that are closer to the loads and distributed through the electricity network [3].

Unlike the conventional distribution system, the DER systems deliver power from a multitude of sources to a multitude of loads, so power network needs to deal with uncontrollable generators. A number of technical issues including the power quality arise when there are multiple uncontrollable sources are involved in a power system.

4. Uncontrollability issues of DER

Electricity generated by DER has shown remarkable growth worldwide. Unlike conventional sources that can provide immediate response to consumer demand, renewable sources cannot provide regular supply adjustable to the demand. Thus, the growth of the decentralized production would mean that the power system has to deal with not only uncontrollable demand but also has to deal with uncontrollable generators. As a result, greater network load stability problems will be created. There are some issues associated with distributed power systems that need to be addressed, but their details are beyond the scope of this paper, such as:

Does DER increase power quality or reduces the power quality; Does DER improve power system's stability or creates stability problem; Does DER increases grid's security or decreases grid's security; Will electricity delivered by DER will cost less or cost more; etc.

Distributed generators such as solar PV power use sun as fuel, freely available but the amount of supplied fuel namely sun radiation are unpredictable, thus the output power of these systems is not constant and in fact is directly proportional to the unpredictable sun conditions. Any changes in the level of sun radiation will cause changes in the amount of power generated by solar power system. The issues with PV and wind power penetration can be limited to the low-voltage networks as the voltage at the medium-voltage network is always very carefully controlled.

5. Why solar energy is important?

Solar PV energy is the most popular among the DER. This is mainly because solar energy is sustainable and widely available almost everywhere. Solar energy technologies use only ordinary materials. Solar energy uses a resource that is far larger than required to provide all of the world's energy. A simple calculation shows that the amount of energy received in one hour by the earth from the sun is equivalent to world energy consumption in one year. Unlike nuclear, solar energy has no security and military risk. Unlike oil and gas, solar energy is available almost everywhere. Unlike fossil fuels, solar energy has minimal environmental impacts. Solar is the most democratic energy technology. No increases in the cost of fuel, routine maintenance is far less than conventional plants, and the fuel (sun energy) does not have to be transported [4].

6. Advantages of grid-connected PV

Grid-connected rooftop solar PV system generates electricity at demand side, so electricity is supplied to the load in most efficient way, and in many cases the generation pattern of solar PV system is consistent with the consumption pattern. Because of the advantages that grid-connected PV has, both power companies and customers are interested in distributed generation system but in different perspective. The utilities are interested in grid-connected PV because they can generate and sell electricity to their customers through their existing network. Large scale grid-connected PV system is seen by some utilities as a means to offset conventional network augmentation. From the electricity users' point of view, the advantage of having grid-connected PV is that they can benefit of having backup generation system. One of the concerns that

utilities have is about the technical issue of grid-connected PV, particularly power quality.

7. Technical issues associate with grid-connected PV systems

As it was mentioned earlier, one of the important issues with grid-connected PV is power quality. Power quality is an important factor from both customer and utility point of view. The power systems are designed to operate at a sinusoidal voltage of a given voltage and frequency. Any significant change in the voltage magnitude, frequency, and purity of the waveform is considered as power quality problem. Power quality is important issue from customer point of view, because the new and modern electrical devices have microprocessor-based controllers and power electronic devices are more sensitive to voltage variations. Variation in sun radiation will result in variation in operating point of solar cell, i.e. variation in operating voltage and current. As the power supply system can only control the voltage but not the currents, therefore every effort must be made to keep the voltage within certain and an acceptable limit to ensure the power quality is maintained, and not affected by the PV generators connected to distribution networks.

Taking roof-top PV in high concentration in terms of number of systems, sometimes the instantaneous power production exceeds the instantaneous power consumption. As a result, the imbalance in power creates a net power flow backwards through the medium voltage to low voltage transformers, meaning that the electric power flows from the low voltage to the medium voltage network, so it is important to determine the limit of penetration level of PV that can be fed into a power network without causing problem to the power system. It is important to know what sets these limits, and what the possibilities of increasing these limits are [5].

Harmonics produced by DER is another issue of concern. Solar PV systems generate direct current, so they need to use an inverter to match with the electrical power system. These inverters produce harmonic currents. In recent years the inverter technology has improved significantly and as a result of this improvement, the level of harmonics produced by inverters has decreased remarkably.

8. Intermittency issues of solar energy

The variable nature of power generation from intermittent sources such as solar PV systems has raised concerns about the ability of providing a reliable power supply. Integration of an energy storage technology causes the intermittent power sources have little effect on the system's operation. To see how high or deep these variations are following figures show these.

Daily variations of sun radiation, solar PV power, wind speed and wind power in three consecutive days in January in Townsville (latitude: 19.3S, longitude: 146.8E) as an example are shown in Figs. 2–5 [6]. Fig. 2 shows solar radiations in those three days. The data shown here are taken from SAM data base. Fig. 3 shows power generated by a 4 kW solar PV system in Townsville. This figure obtained by running SAM simulation program. Fig. 4 shows variation of wind speed in the same three day of the same location, while Fig. 5 shows power generated by a 330 kW wind turbine. Fig. 5 obtained by running a simulation program developed by the author using wind speed data from SAM. As one can see variation of wind power follows variation of wind speed but much sharper and deeper compared with variation of PV power. This is mainly because that PV power is proportional to the amount of sun radiation but wind power is proportional to cube of wind speed [9]. This is clearly can be seen comparing Fig. 4 with Fig. 5.

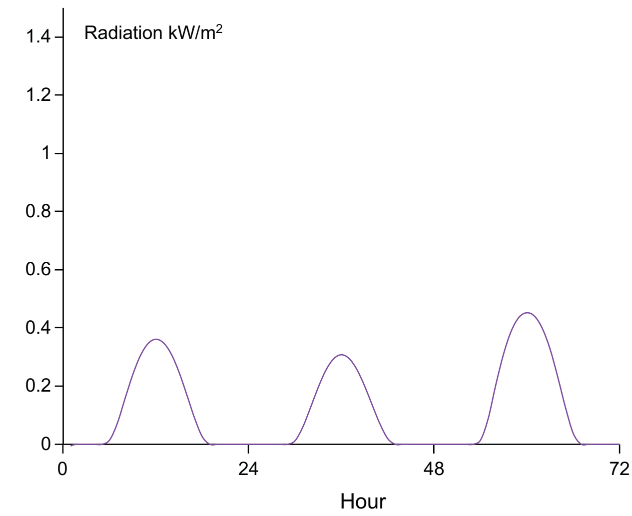

Fig. 2. Variation of radiation.

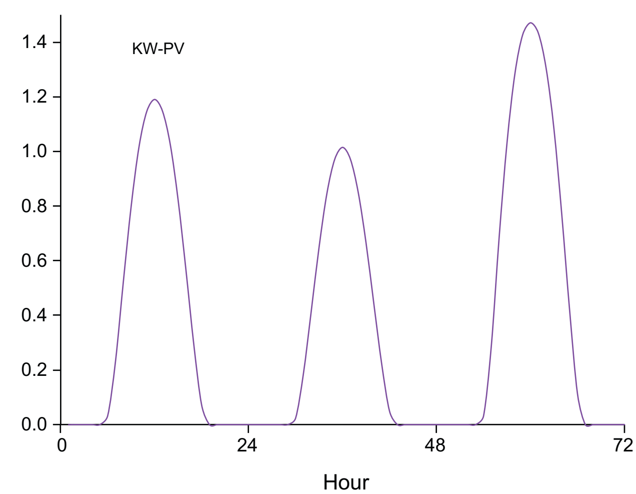

Fig. 3. Variation of solar power, 4 kW PV system.

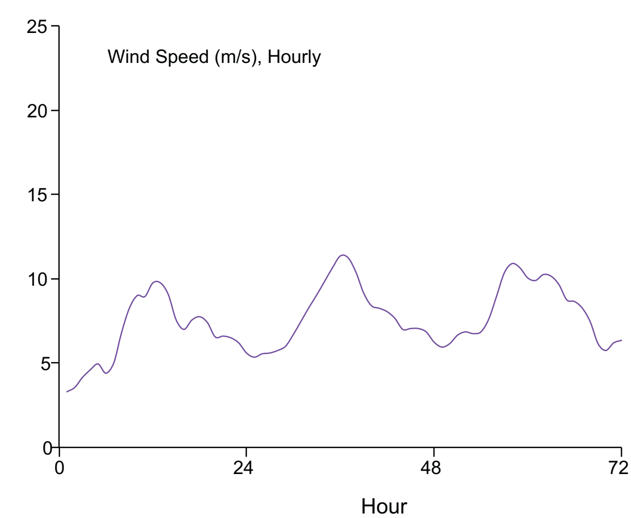

Fig. 4. Variation of wind speed.

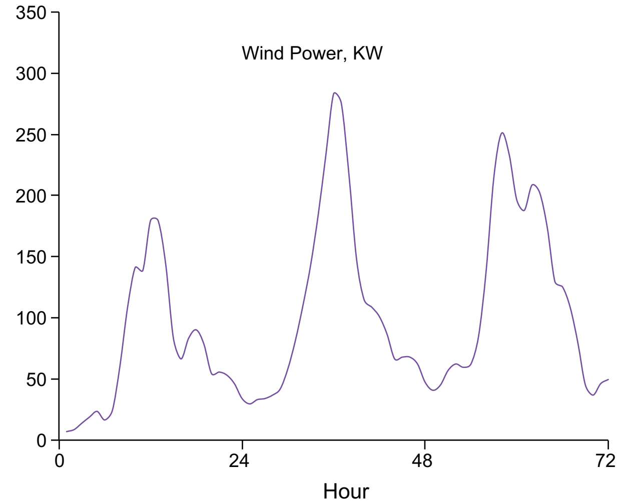

Fig. 5. Variation of wind power for a 330 kW.

9. Role of energy storage technology

Energy storage and demand side management are two options that can be used to increase the penetration level of grid-connected distributed generation. The fact is that energy generation from renewable energy is seldom constant over time and also electricity demand is never constant. Therefore, using an energy storage technology into renewable energy generating system is important.

For decades, people have argued that electricity differs from all other products and markets because it cannot be stored. This has been basically correct, but future developments have the potential to remove this constraint and to combine storage with other energy technologies to create a new energy paradigm.

Energy storage technologies provide opportunity for the generation side to meeting the level of power quality as well as reliability required by the demand side. Energy storage can also provide emergency power and peak shaving opportunity. Energy storage is especially important for decentralized power supply system by giving the more load-following capability, which is an important factor from generation side management.

10. Electricity storage systems

There are many different technologies available for storing energy; they come in all forms of energy such as mechanical, chemical, and thermal. Following energy storage devices have been explored, they are matured and leading the storage technologies [7]:

Battery storage; pumped hydro storage; thermal energy storage; compressed air energy storage; energy storage using flow batteries; electrolyzer and fuel cell; flywheel energy storage; superconducting magnetic energy storage; super-capacitors.

In terms of their applications, the energy storage technologies are divided in two categories:

- Low to medium power application to be used in isolated areas. These two categories are used where the energy could be stored as kinetic energy, chemical energy, compressed air, hydrogen, or in super-capacitors.
- Large scale power applications where the energy could be stored as potential energy, thermal energy, chemical energy (flow batteries), or compressed air.

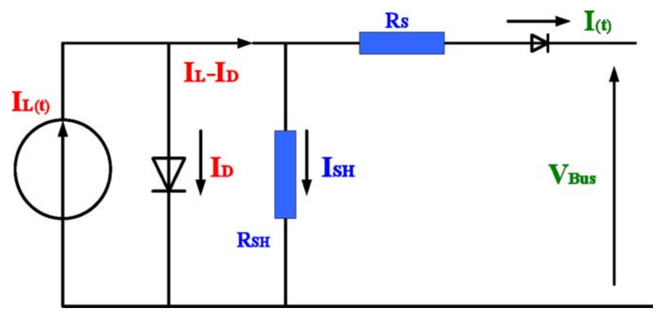

Fig. 6. Equivalent circuit of a practical PV cell.

11. Characteristics of energy storage techniques

Storage technologies are characterized by factors such as: storage capacity; available power; depth of discharge or power transmission rate; discharge time; efficiency; durability (cycling capacity); self-discharge; mass and volume densities of energy; monitoring and control equipment; operational constraints; reliability; environmental aspect; other characteristics. Energy storage can increase performance ratio of the PV system. Energy storage helps to reduce power injection to the grid during the peak times. Grid-integration of solar PV, supported by storage device is focus of this study. In this study, a PV panel is supported by a super-capacitor and a battery.

12. Solar PV combined with battery and super capacitor

Practical solar cell model requires inclusion additional parameters into the basic model. These parameters are series resistance R_S and shunt resistance R_{SH}. Electrical circuit of a practical model is shown in Eq. (1). The equivalent circuit of super-capacitor is shown in Eq. (2). The resistor R_{SC} is the equivalent series resistance, which is in the range of mΩ, and R_{PC} is an inner equivalent parallel resistance, which is in the range of hundreds of kΩ.

Fig. 6 shows electrical circuit of solar PV.

Fig. 7 shows electrical circuit of super-capacitor.

Fig. 8 shows electrical circuit of all components, i.e. solar PV, battery, super-capacitor, and load.

R_{SC} consists of electrode resistance, electrolyte resistance and contact resistance that waste power for internal heating when charging and discharging in capacitor. R_{PC} is responsible for leakage current, when super-capacitor is in stand by mode.

Mathematical model of the practical PV cell model is expressed in Eq. (1) [8].

$$I(t) = I_L - I_O(e^{V+IR_S/\alpha V_T} - 1) - \frac{V + IR_S}{R_{SH}}. \qquad (1)$$

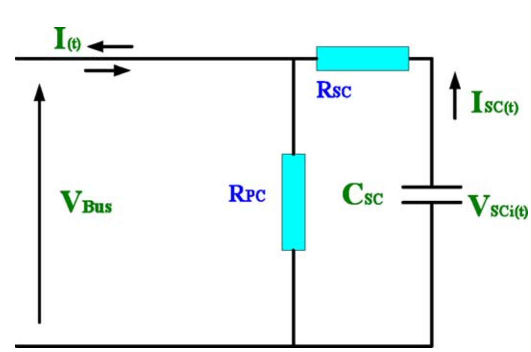

Fig. 7. Equivalent circuit of a super-capacitor.

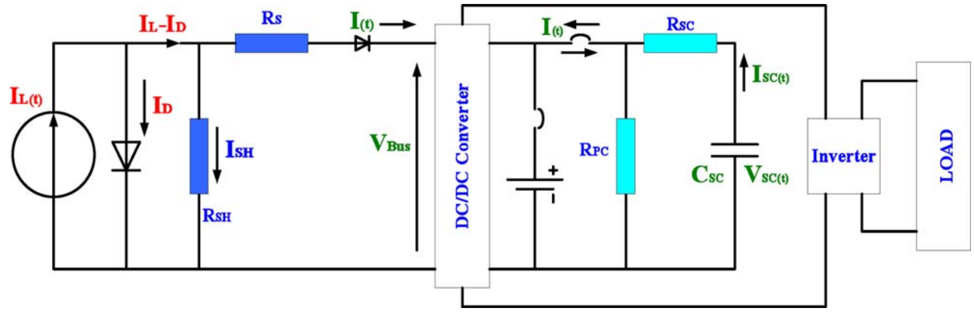

Fig. 8. Equivalent circuit of solar PV module and super-capacitor.

At super-capacitor side:

$$I_{(t)} = V_{Bus}\left(\frac{1}{R_{PC}} + \frac{1}{R_{SC}}\right) - \frac{V_{SC(t)}}{R_{SC}} \tag{2}$$

$$V_{SC(t)} = V_{Bus}\left(1 - e^{-t/\tau}\right). \tag{3}$$

$$\tau = R_{SC}\,C_{SC}. \tag{4}$$

13. Conclusions

This paper has reviewed conventional power structure, their weaknesses and inability to meet the growing demand for electricity and meet response to increasing concern about environmental issues associated with current network. Attentions have now been turned to decentralized smaller size generators using alternative sources. Due to intermittent nature of alternative sources such as solar the generated by this source continuously fluctuate. Storage devices can help to reduce or eliminate these variations.

Storage devices can play a major role in the process of integration of alternative sources in decentralized power networks. Storage is not only is a technical solution for network management, ensuring real-time load levelling, but it is also a mean of better utilizing renewable resources by avoiding load shedding in times of overproduction. Despite the fact that this paper has not described in detail all the characteristics of the different storage technologies, but it has shown that the possibility of storing electrical energy exists, whenever they are needed in any quantity. This paper also has presented a model for a combined solar PV with battery and super-capacitor.

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